Enhancing Coverage and Reducing Power Consumption in Peer-to-Peer Networks Through Airborne Relaying

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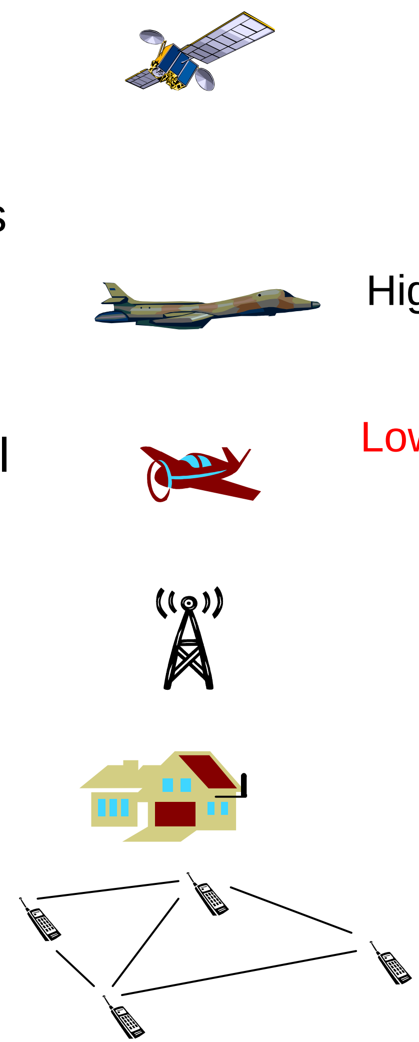
Outline

- Introduction
- Radio link model
- Power consumption for LoS channels
- Performance in practical radio channels
- Conclusions

Introduction (1/2)

- Radio nodes of various heights are used in mobile communications.
- An airborne vehicle 100’s to 1000’s of meters above the surface experiences better channel conditions compared to a terrestrial mobile platform.
- The airborne nodes can be rapidly deployed at low cost, compared to HAP and satellite units.
- We consider an urban network over a radius up to 500m.



Satellite
(100’s-10^5’s km)

High altitude platform (HAP)
(around 22km)

Low/Medium altitude platform
(100’s/1000’s meters)

Tower
(10’s of meters)

Roof-level nodes
(around 10 meters)

Ground mobiles
(sensor, handset, vehicle, etc.)

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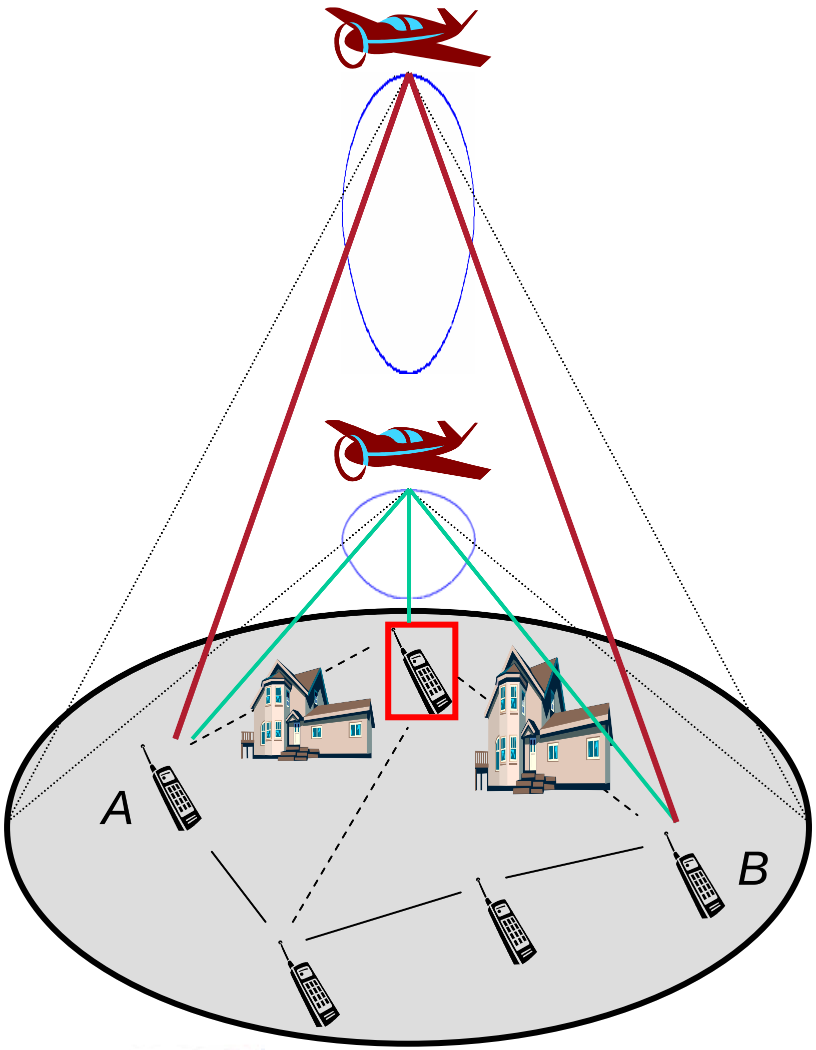
Introduction (2/2) – Air relay



Pros:

- High-gain directional air antenna
- High likelihood of LoS
- Reduced pathloss and less severe fading in NLoS (compared to a terrestrial link)

Cons:

- Large Tx-Rx distance, thus high LoS pathloss

Problems:

- Air antenna gain – LoS pathloss Trade-off?
- Practical urban environment:
  coverage, connectivity,
  power consumption?

Radio link model (1/2)

Received mean signal power

$$P_R = \frac{P_T G_T G_R}{L_0 L_b L_s}$$

where

P_T – transmit power

G_T – transmitter (Tx) antenna gain

G_R – receiver (Rx) antenna gain

L_0 – circuit loss

L_b – mean pathloss

L_s – shadowing

Three equivalent expressions

- $P_R \geq \gamma_{th}$
- $MTPL = \dfrac{P_T G_T G_R}{L_0 \gamma_{th}} \geq PL = L_b L_s$
- $MTPL_{rev.} = \dfrac{P_T G_R}{L_0 \gamma_{th}} \geq EIPL = \dfrac{L_b L_s}{G_T}$

where

γ_{th} – threshold at the receiver

MTPL – maximum tolerable path loss

$MTPL_{rev.}$ – revised MTPL

EIPL – effective isotropic path loss from the transmitter

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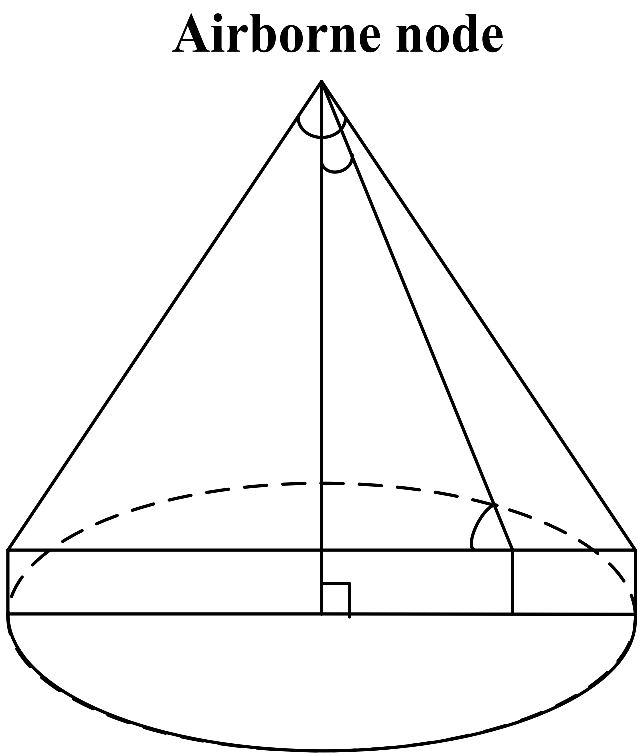
Radio link model (2/2)



Directional air antenna gain:

$$G_A(R, h_t, r) \approx \frac{9.1385}{\Theta_{3dB}^2[\mathrm{rad}]} \cos^m \vartheta$$

where

$$\Theta_{3dB} \approx 2 \tan^{-1}(1 / k)$$

$$m = \ln 2 / \ln \sec(\Theta_{3dB} / 2)$$

$$\cos \vartheta \approx k / \sqrt{k^2 + \tau^2}$$

$$k = h_t / R$$

$$\tau = r / R$$

assuming $h_t >> h_r$.

Power consumption for LoS channels (1/2)

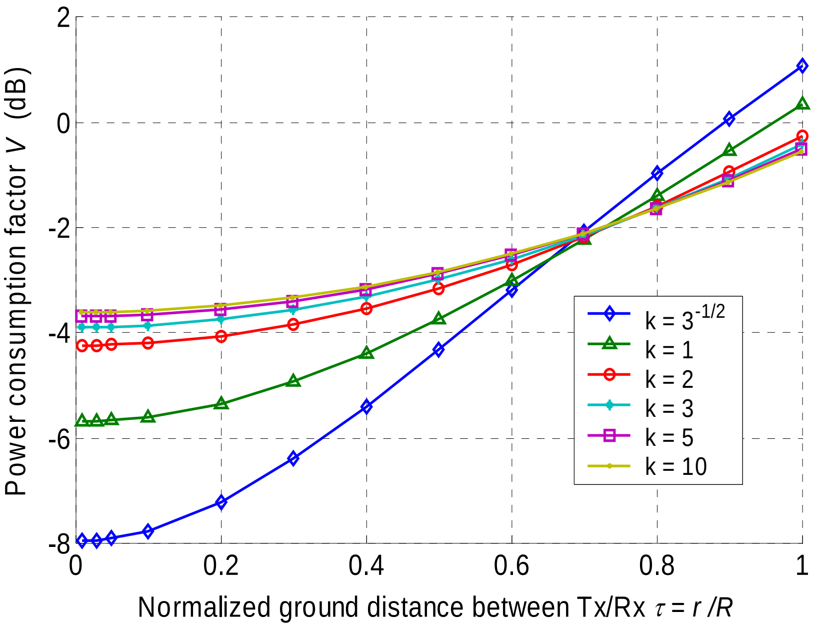
- Power consumption is the transmit power. EIPL from an air Tx determines the transmit power:

$$\boldsymbol{EIPL}_A[\text{dB}] = 20 \log \frac{4\pi}{\lambda} + 20 \log \boldsymbol{R} + \boldsymbol{V}$$

where V is power consumption factor. When $k \geq 3$,

$$V[\text{dB}] \approx -3.588 + 3\tau^2$$

- Given a service area, when $h_t \geq 3R$, increasing the height of the airborne node does not significantly change the power consumption; it may however improve the likelihood of LoS.



- Given an operating area, we may decide on the optimal height of the air node based mainly on the likelihood of LoS.

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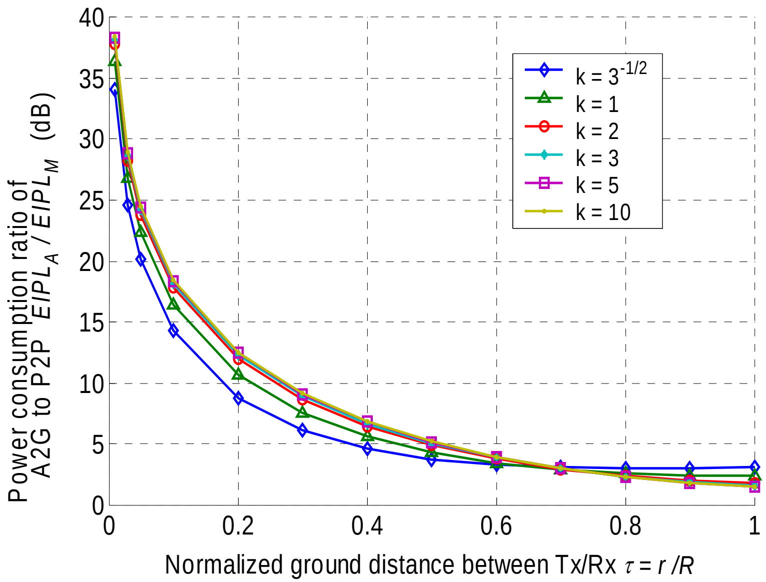
Power consumption for LoS channels (2/2)

- Ratio of EIPL between A2G and P2P links:

$$\frac{EIPL_A}{EIPL_M}[\mathrm{dB}] \approx -3.588 + 3\tau^2 - 10\log\tau^2 + G_{T,M}$$

when $k \geq 3$, where $G_{T,M}$ is the mobile Tx antenna gain.



- An A2G LoS link has no advantage in terms of power consumption in a free-space channel.
- However, P2P LoS propagation only exists over very short distances according to the ground-reflected pathloss model.
- Therefore, at longer distance, we have two options: use multihop P2P relays (if available), or use air relays to reduce the number of hops at the cost of affordable extra LoS pathloss (much less than NLoS pathloss).

Practical channel (1/4) - Local coverage

- Local coverage for a single channel category (e.g. NLoS)

$$
\begin{aligned}
F_l &= \mathbf{P}\left(P_R \geq \gamma_{th}\right) \\
&= \mathbf{P}(MTPL \geq L_b + L_s) \\
&= \mathbf{P}(MTPL_{rev.} \geq L_b + L_s - G_T)
\end{aligned}
$$

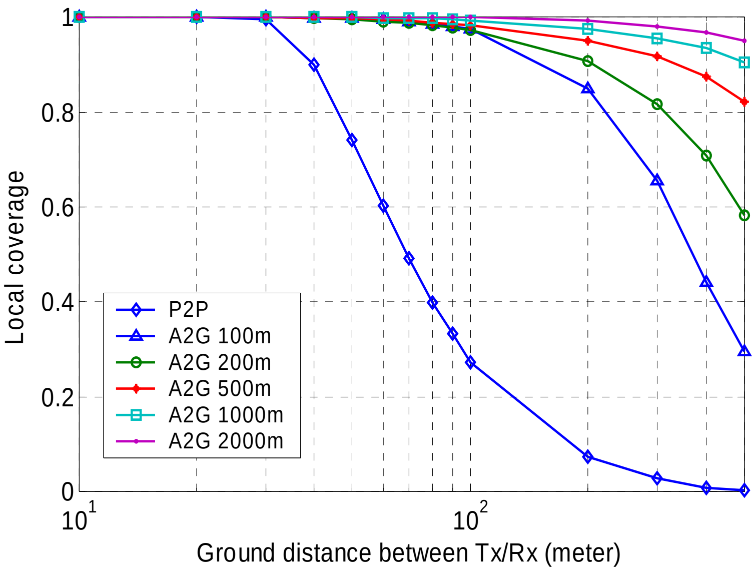
- Local coverage for a radio channel in a practical environment

$$F_l = \sum_i P_{ch\ i} \mathbf{P}(L_{s,ch\ i} \leq MTPL_{rev.} + G_T - L_{b,ch\ i})$$

where

$P_{ch\ i}$ – probability of occurrence of channel category i;

$L_{s,ch\ i}$, $L_{b,ch\ i}$ – shadowing and MPL for channel category i.



$MTPL_{rev.}$ = 100dB, R = 500m

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Practical channel (2/4) - Area coverage

- Area coverage is the statistical average of local coverage within a service area.

$$F_a = \int_r p(r) \cdot F_l dr$$

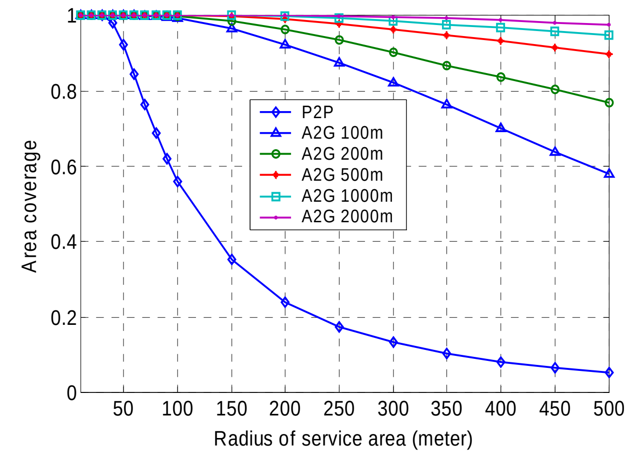
where *p(r)* is the probability density function (PDF) of the distance between an arbitrary point and the transmitter.

- For a disk shaped area with radius *R*, assuming the transmitter is located in the centre:

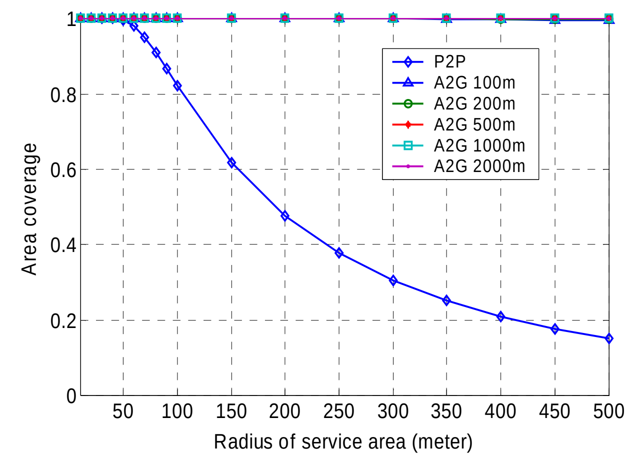
$$p(r) = \frac{2r}{R^2} \qquad 0 \le r \le R$$

- Then, area coverage for such a scenario is:

$$F_a = \frac{2}{R^2} \int_0^R r F_l dA$$



$MTPL_{rev.}$ = 100dB



$MTPL_{rev.}$ = 120dB

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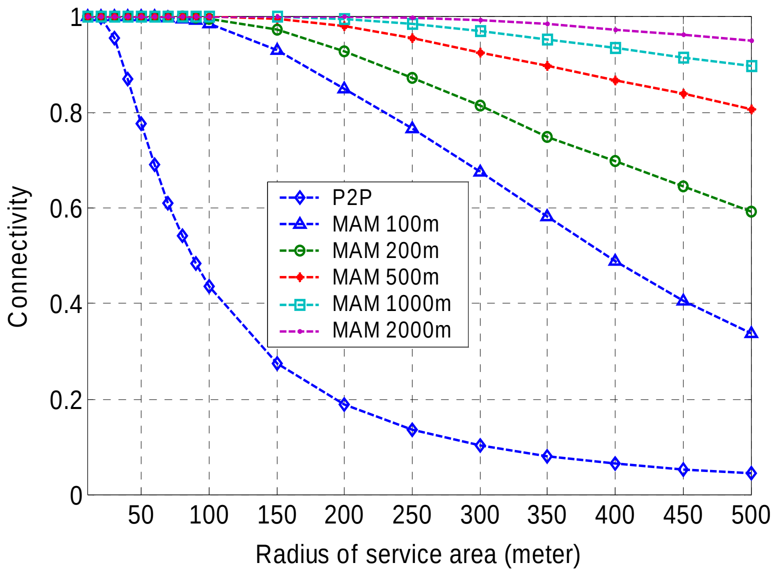
Practical channel (3/4) - Connectivity

- Coverage is closely related to the connectivity (the probability of a successful connection between two nodes) from the networking aspect.
- For a P2P network with uniformly distributed mobiles in a disk area with radius *R*, the PDF of the distance *r* between two arbitrary nodes is given by

$$p(r) = \frac{4r}{\pi R^2}\cos^{-1}\left(\frac{r}{2R}\right) - \frac{2r^2}{\pi R^3}\sqrt{1-\frac{r^2}{4R^2}}$$

thus P2P direct connectivity can be computed.



$MTPL_{rev.}$ = 100dB

- The advantage of higher coverage for an air node leads to higher mobile-air-mobile (MAM) relayed connectivity than P2P direct connectivity .

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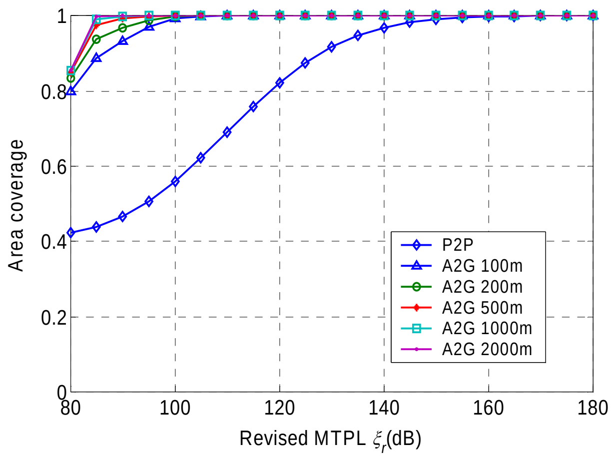
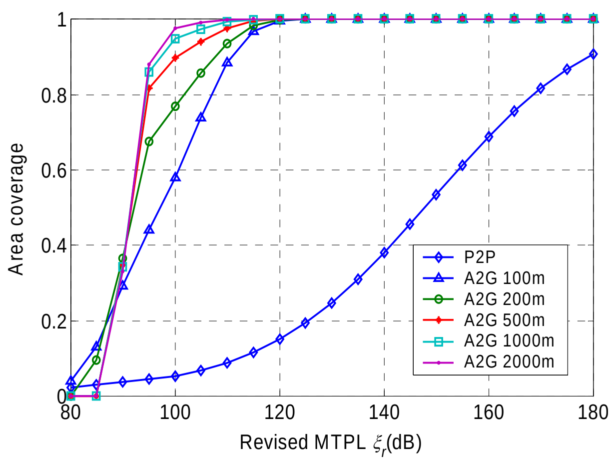
Practical channel (4/4) - Power consumption



R = 100m



R = 500m

- In a small area, a mobile node has good coverage, but an air node can save a significant degree of transmit power, and has better coverage when the transmit power is constrained.
- For a larger area, the coverage of a mobile node is often too low for practical transmit power levels.
- Therefore, an air relay can reduce transmit power compared to P2P communications, as well as improve connectivity when mobile nodes are sparsely distributed.

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Conclusions

- Compared to P2P links, A2G links have the following desirable features:
  - a high likelihood of LoS,
  - less severe shadowing in NLoS propagation,
  - a high-gain directional air antenna,
- Hence, air nodes offer good urban coverage.
- Therefore, air relays have the following advantages
  - Improved connectivity,
  - reduction in the number of relay hops,
  - reduction in transmit power.
- Air nodes are best used for
  - long-hop relays,
  - reducing coverage 'holes' in sparse mobile networks over a large area,
  - emergency scenarios, sink node for wireless sensor networks, etc.

Questions?

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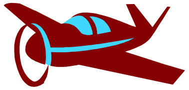

Thank you for you attention!

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